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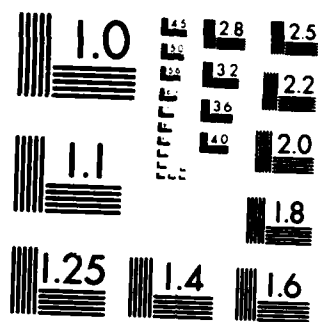
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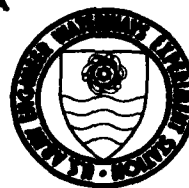
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# AN EVALUATION OF METHODS FOR MEASURING SURFACE TEMPERATURE

by

Gunter Hübner, Curtis L. Gladen

Environmental Laboratory

U. S. Army Engineer Waterways Experiment Station  
P. O. Box 631, Vicksburg, Miss. 39180

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20. ABSTRACT (Continued).

radiation thermometers were found to depend on target emissivity, sky temperature, and spectral range of instrument. Measurements of kinetic temperature depended on surface contact of the probe and on the amount of surface disturbance. Any comparison between different temperature measurement techniques should take these influences into account.



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## PREFACE

The work reported herein was conducted at the U. S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss., from March to December 1981 as a portion of Work Unit 010, "Field Experiments for Generation and Testing of Design Criteria for Fixed Installation Camouflage," Task CO, "Theater of Operations Construction," Project No. 4A762719AT40, "Mobility and Weapons Effects Technology."

The study was conducted under the general supervision of Dr. John Harrison, Chief, Environmental Laboratory, and Mr. Bob O. Benn, Chief, Environmental Systems Division, and under the direct supervision of Dr. Lewis E. Link, Chief, Environmental Constraints Group (ECG). The experiment was run by Dr. Gunter Hübner and Curtis L. Gladen, ECG. Dr. Hübner from Industrieanlagen-Betriebsgesellschaft, Ottobrunn, West Germany, was working at WES under a government-sponsored scientific exchange program. The report was prepared by Dr. Hübner and Mr. Gladen.

Commanders and Directors of WES during this study were COL Nelson P. Conover, CF, and COL Tilford C. Creel, CE. Technical Director was Mr. F. R. Brown.

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## AN EVALUATION OF METHODS FOR MEASURING SURFACE TEMPERATURE

### PART I: INTRODUCTION

#### Background

1. The U. S. Army Engineer Waterways Experiment Station (WES) is the lead laboratory of the Corps of Engineers for the camouflage of fixed installations. With the advent of sensors operating in the thermal infrared part of the electromagnetic spectrum, camouflage in the thermal infrared has become increasingly important (Link 1979).

2. The Environmental Systems Division of the WES Environmental Laboratory is developing tools to characterize targets and backgrounds in the thermal infrared. These tools comprise instrumentation to measure temperature and computer models to predict temperature.

3. Among the computer models, are the:

- a. Terrain Surface Temperature Model (TSTM) to predict the surface temperature of nonvegetated surfaces (Balick et al. 1981).
- b. VEGIE, a module run in conjunction with TSTM to predict ground and vegetation temperatures for areas of lawn, pasture, and rangeland (Balick, Scoggins, and Link 1981).
- c. Vegetation Canopy Thermal Model (VCTM) to predict the effective radiative temperature of a canopy such as forest as seen from above at various viewing angles (Smith et al. 1981).

4. To validate the thermal models, a variety of surface temperatures were measured in Zweibrücken, West Germany, in 1979 and 1980 and in Moab, Utah, in 1981. Instrumentation used included thermistors, thermocouples, several radiation temperature probes, and three types of thermal imaging systems.

5. During the evaluation of these measurements, inconsistencies between the different types of temperature measurements and the temperatures predicted from computer models became apparent. An example for grass temperature is given in Figure 1, which shows a model prediction

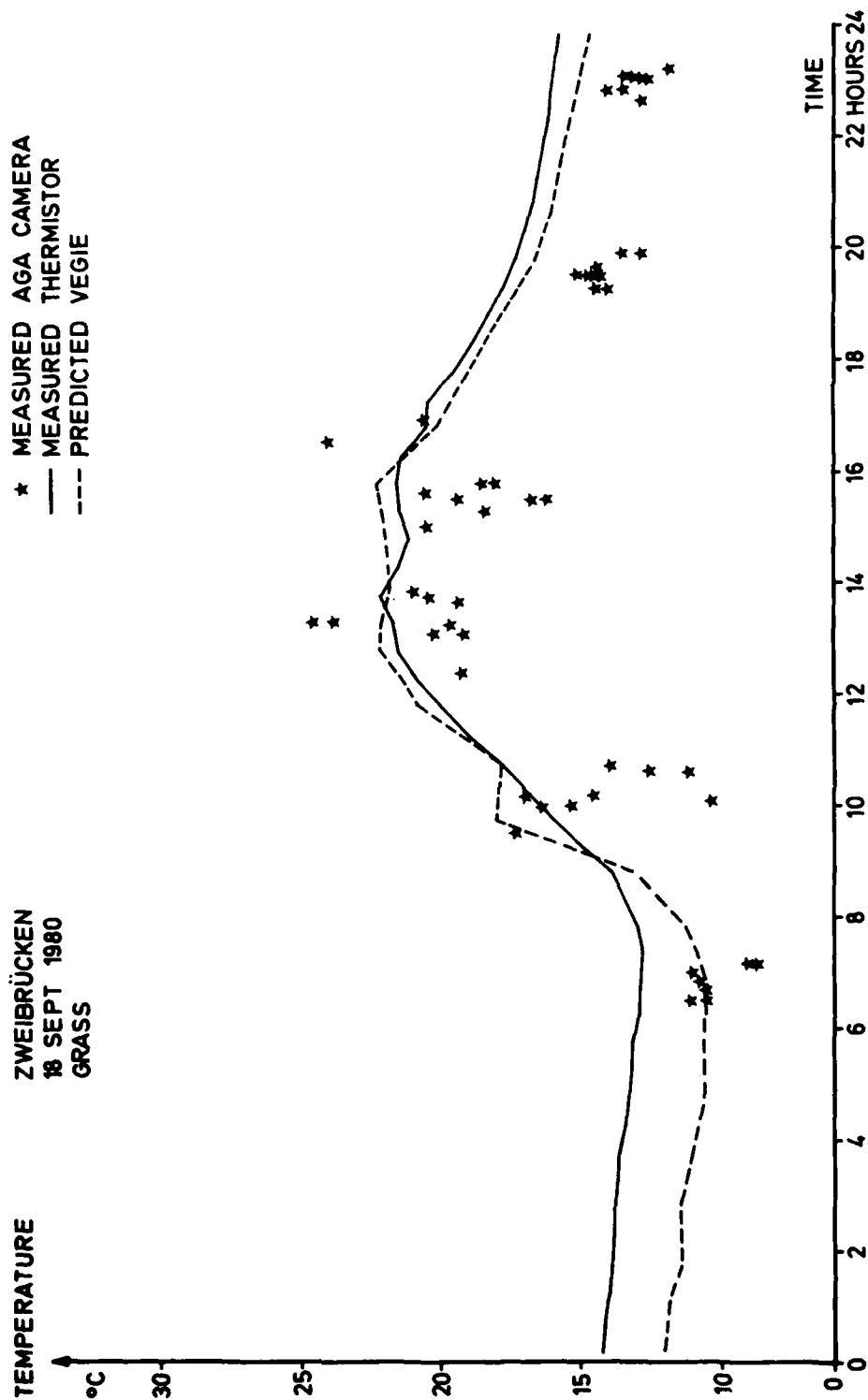


Figure 1. Measured and predicted grass temperatures from an experiment in Zweibrücken, West Germany

and two types of temperature measurements: a thermistor measurement from one spot and data from a thermal imaging system from several locations in the vicinity. The results differ considerably, and it is not clear how to validate a model prediction with these data.

#### Purpose and Scope

6. A small-scale experiment was run in Vicksburg, Miss., to clarify some possible influences on the measurements. A simple target was measured with different instruments simultaneously. Model predictions had cast doubts on the way the thermistors were installed in Zweibrücken in 1980, i.e., with a small sun shield and a thermally conducting silicone paste. The paste turned out to be hygroscopic, which might have affected the temperature measurement. Radiometric measurements were collected manually at Zweibrücken. To improve reproducibility and to obtain more frequent measurements, readout of the instruments was automated. In addition, a newly acquired data logger was to be tested.

## PART II: CONCEPTS OF TEMPERATURE MEASUREMENTS

7. Any meaningful comparison between types of temperature measurements has to be based on an understanding of the different concepts involved. Three parameters can be identified to characterize surface condition in the thermal infrared:

- a. Kinetic temperature.
- b. Spectral emission.
- c. Radiation temperature.

While the first two parameters are easy to understand, radiation temperature is a more involved concept and--as shall be seen--is dependent on extraneous influences.

8. Kinetic temperature describes the movement of the surface molecules and can be measured with a probe contacting the surface, such as a thermocouple or a thermistor. Advantages of this type of measurement are that it can be easily automated to provide data over extended periods and that it is independent of the background. Disadvantages are that it disturbs the surface and that it does not measure directly the energy perceived by an electromagnetic sensor.

9. All surfaces emit thermal radiation as a function of their kinetic temperatures. In addition, the surface reflects some of the background radiation. Their sum, emission plus reflection, has a certain spectral distribution, which can be measured with a spectroradiometer as a function of wavelength (Hübner 1982). Measurements of spectral emission are complicated and require sophisticated equipment. They are usually done for selected targets only or to determine the emissivity of a surface.

10. The sensors used to detect and recognize targets in the thermal infrared are integrating sensors. Rather than measure the spectral distribution of the radiation received from the target, these sensors measure the total intensity integrated over a part of the spectrum. The selected part depends on the sensitivity of the particular detector used plus any filters in the sensor to block unwanted wavelengths.

Wavelength regions often used in the thermal infrared are, e.g., 3 to 5, 8 to 14, and 10 to 12  $\mu\text{m}$ .

11. The signal output  $U$  of the sensor is proportional to the intensity received by the detector. It can be written as

$$U = \int_{\lambda_1}^{\lambda_2} \{ \epsilon(\lambda) \rho(\lambda, T) + [1 - \epsilon(\lambda)] \rho_B(\lambda, T_B) \} R(\lambda) d\lambda \quad (1)$$

where

$\lambda_1, \lambda_2$  = sensitivity limits of detector

$\epsilon(\lambda)$  = emissivity of target

$\rho(\lambda, T), \rho_B(\lambda, T_B)$  = spectral radiance of target and background

$1 - \epsilon(\lambda)$  = reflectance of target

$R(\lambda)$  = response curve of detector

The spectral radiances  $\rho$  and  $\rho_B$  can be calculated from Planck's radiation law as a function of kinetic temperature.

12. To simplify Equation 1, the following assumptions are made. Let the detector be ideal, that is, respond equally to all wavelengths:

$$\lambda_1 = 0, \lambda_2 = \infty, R(\lambda) = R = \text{constant}$$

In addition, let the emissivity of the target be constant. The integration can be evaluated in closed form and yields:

$$U = R\epsilon\sigma T^4 + (1 - \epsilon)\sigma T_B^4 \quad (2)$$

where

$$\sigma = 5.672 \cdot 10^{-8} \text{ W/m}^2\text{K}^4 \text{ (Stephan-Boltzmann constant)}$$

$T$  and  $T_B$  = temperature of target and background, respectively, Kelvins

If in addition, it is assumed that the emissivity is large, then the second part of the sum can be neglected and one obtains:

$$U = R\epsilon\sigma T^4 \quad (3)$$

13. Equation 3 provides the justification for the definition of

radiation temperature. An ideal black body would radiate the maximum intensity for a given temperature  $T_{BB}$  and yield the signal:

$$U = R\sigma T_{BB}^4, \quad \epsilon = 1 \quad (4)$$

The nonideal target ( $\epsilon < 1$ ) radiates according to Equation 3. Radiation temperature  $T_r$  of the target is defined as the temperature at which a black body would radiate the same intensity:

$$U = R\sigma T_r^4 \quad (5)$$

Combining with Equation 3 gives

$$T_r^4 = \epsilon T^4 \quad (6)$$

According to Equation 6, the radiation temperature to the fourth power equals the kinetic temperature to the fourth power times the emissivity.

14. All broadband thermal sensors like radiation thermometers or thermal imaging systems yield a signal output  $U$  that can be converted by Equation 5 or a similar calibration curve to a radiation temperature. If the surface emissivity  $\epsilon$  is known, the kinetic temperature  $T$  can be determined from Equation 6. Difficulties arise from the fact that the assumptions made in deriving Equations 5 and 6 are not valid in many cases.

15. If the emissivity is not close to one, reflection of the background cannot be neglected. To retain the concept of radiation temperature, Equation 5 is expanded to include reflection of the background (temperature  $T_B$ ), resulting in:

$$T_r^4 = \epsilon T^4 + (1 - \epsilon) T_B^4 \quad (7)$$

It should be pointed out that the radiation temperature of Equation 7 is no longer a parameter describing only the target. It also depends on the background temperature.

16. Real detectors do not fulfill the assumptions made above. If the emissivity of the target is independent of wavelength, and the response curve of the detector is known, the integral in Equation 1 can be evaluated. The result is no longer proportional to the fourth power of the temperature, but will be a more complicated function of the detector, such as  $f_D(T)$ .

$$T_r^4 = \epsilon f_D(T) + (1 - \epsilon) f_D(T_B) \quad (8)$$

The radiation temperature defined in Equation 8 is a function of kinetic target temperature and target emissivity, but it also depends on background temperature and on the specifics of the instrument used. It is quite possible that two different instruments would measure different radiation temperatures for the same target and background.

17. In a fully enclosed laboratory, the background is made up by the surrounding walls. Often the walls all have the same temperature. Their effective emissivity equals one, which is true for all enclosures of constant temperature. Hence, the background radiation can easily be measured and included in Equation 8. In outdoors measurements, however, the background is more complex. It consists of nearby surface features plus the sky. Their relative contribution will depend on target surface orientation and on the directional reflectance of the target. For horizontal target surfaces, the background radiation will be mainly sky radiation.

18. The effective radiation temperature of the sky depends primarily on air temperature and cloud cover. Under a heavily overcast sky, radiation temperature of the sky approximates air temperature. Under clear skies, sky temperature is well below air temperature. There are several empirical formulae that relate sky temperature to air temperature for clear sky (Jacobs 1980). However, these models describe the total energy exchange and would be applicable only to a very broadband detector, sensitive from 2 to 20  $\mu\text{m}$ . Most detectors are sensitive within a much narrower band.

19. In the spectral region from 2 to 20  $\mu\text{m}$ , there are several

bands where the atmosphere changes between strong absorption of radiation and high transmission. In the absorption bands, the detector senses a sky of essentially air temperature. In the so-called infrared windows, wavelength bands with high transmission, the detector senses radiation from space that has a very low effective temperature. This means that the effective sky temperature measured by a detector depends on the shape of the response curve of the detector, the critical question being whether the detector is sensitive to wavelengths outside the infrared windows. Often, sensors are equipped with filters to suppress detector sensitivity outside the windows.

20. It has been shown that the broadband formula found in the literature cannot be used to predict the sky radiation temperature measured with a particular sensor. Until better models become available, it will be necessary to measure sky temperature with the same detector as used for target temperatures. Many field experiments have been run where the measurement of sky temperature was neglected, making the interpretation of surface radiation temperature exceedingly difficult.

21. However, radiation thermometers have several significant advantages over contact thermometers. The main advantage is that they do not disturb the surface to be measured in any way. No surface preparation is required to ensure good contact. The temperature of features that do not have a closed surface such as a fluffy carpet, a lawn, or the edge of a forest can be measured in a meaningful way only with radiation thermometers. Radiation thermometers respond very quickly, whereas contact thermometers have a longer response time. Radiation thermometers can be operated at a distance from the target, thus permitting rapid measurements of many features in the vicinity of a central data station. Their ease of operation has made them very popular in recent years.

### PART III: MEASUREMENT OF SURFACE TEMPERATURE

#### Thermometers Used

22. Two types of contact thermometers and two different radiation thermometers were used in the WES experiment described herein:

- a. Campbell Scientific Thermistor Model 101.
- b. Wahl Digital Heat-Prober Model 350X.
- c. Wahl Heatspy Digital Infrared Thermometer.
- d. Telatemp Infrared Thermometer.

Characteristic data of these instruments are summarized below.

23. The Campbell Scientific Thermistor Model 101 incorporates a Fenwal Electronics UUT51J1 thermistor in a water-resistant probe with 10-ft (3.05-m) shielded leads. The probe contains a 249-k $\Omega$ , 0.5 percent pickoff resistor that is molded into the termination end of the thermistor leads. The probe tip has a white-colored plastic encapsulation measuring 5 cm in length and 5 mm in diameter. The cylindrical shape of the probe is designed to measure temperature in air or soil. Surface temperatures are measured by taping the probe onto the surface. The probe requires a direct current (DC) excitation. The voltage drop across the pickoff resistor provides the output signal, which is a highly non-linear function of temperature. A fifth-order polynomial is used to linearize the output resulting in the following errors:

Maximum system error (probe plus digitizing)

$\pm 0.4^{\circ}\text{C}$  from  $-20^{\circ}$  to  $+35^{\circ}$

$\pm 0.5^{\circ}\text{C}$  from  $-30^{\circ}$  to  $+53^{\circ}$

$\pm 0.7^{\circ}\text{C}$  at  $-40^{\circ}$

$\pm 0.6^{\circ}\text{C}$  at  $+60^{\circ}$

Linearization fit

$\pm 0.1^{\circ}\text{C}$  from  $-35^{\circ}$  to  $+47^{\circ}$

$+0.8^{\circ}\text{C}$  at  $-40^{\circ}$

$-0.9^{\circ}\text{C}$  at  $+55^{\circ}$

24. The Wahl Digital Heat-Prober Model 350X is a battery-operated, hand-held instrument that determines temperature through measuring the

resistance of a platinum wire. The resistance element has a nominal resistance of 100 k $\Omega$  at 0°C and a temperature coefficient of 0.00385 k $\Omega$ /°C. Probe tips are interchangeable. Probes for measuring surface temperature have a flat circular platinum tip of 6.4 mm diameter. A thermally conducting paste can be used to ensure good contact between probe and surface. Response time of the probe is 2 sec to 63 percent of final reading. The digital display provides a temperature readout in degrees centigrade with a resolution of 0.1°C. Accuracy with the instrument at ambient temperature of 25°C is  $\pm 0.5$  percent  $\pm 1$  digit of readout. This accuracy changes by 0.02°C/°C change in ambient temperature. Repeatability of measurements is  $\pm 0.2^\circ\text{C} \pm 2$  digits.

25. The Wahl Heatspy Digital Infrared Thermometer is a hand-held spot radiometer. It collects infrared radiation between 4.8 and 20  $\mu\text{m}$  with fixed focus optics onto a thermopile detector. The thermopile measures the temperature difference between the target and the instrument. Instrument temperature is established with an additional thermistor and its readings are added to that of the thermopile. Whenever the instrument temperature changes, the zero setting of the thermopile has to be manually adjusted. Temperature is read out on a digital display with a resolution of 1°C. If the output jack is used to drive an external recorder, temperatures can be obtained at a resolution of 0.3°C. Accuracy of reading and repeatability are both 0.5 percent of full scale at ambient temperature of 25°C. The gain of the detector amplifier can be adjusted manually so as to simulate the effect of varying target emissivities. Spot size viewed by the radiometer is 5 cm in diameter at distances up to 1.20 m with a 3.5-deg field of view beyond 1.20 m.

26. The Telatemp Infrared Thermometer is a spot radiometer similar to the Heatspy but with the following differences. Zero setting of the instrument is done automatically and updated twice every second. A filter restricts the spectral sensitivity of the radiometer to wavelengths between 8 and 14  $\mu\text{m}$ . Resolution of the digital display is 0.1°C. An additional sensor measures air temperature at the front of the instrument. The display shows either target temperature or the temperature difference between target and air.

### Design of the Experiment

27. An old asphalt test plot, 4 m  $\times$  10 m, was selected as the target. The plot, located on the grounds of WES, was surrounded by weeds with bushes and trees at a distance. A 1- by 1-m section of the asphalt was painted white to obtain two similar targets, but with different surface properties. In the experiment, surface temperatures of the two sections were to be measured with thermistors and with radiation thermometers so that the results from different instruments could be compared.

28. Four types of deployments were tested for the thermistors. They were taped onto the surface with and without sun shields, with and without heat conducting silicone paste between thermistor and surface. This required a total of eight thermistors for the two test sections. The two radiation thermometers, the Heatspy and the Telatemp, were mounted on tripods. From a distance of 50 cm, they viewed the same spot on the unpainted asphalt near the thermistors. Both instruments were turned on and connected to battery chargers supplied by the manufacturer. Output from the radiometers and the four thermistors with paste was recorded on a data logger Campbell Scientific CR 21. The unit was programmed to collect data averaged over 5-, 30-, and 60-min intervals. The four thermistors without paste were connected to a Poly-corder data logger from Omnidata International. The unit recorded instantaneous values every 5 min.

29. An automatic weather station was set up on the asphalt plot that measured:

- a. Air temperature.
- b. Relative humidity.
- c. Total solar insolation.
- d. Wind speed.
- e. Wind direction.
- f. Total downwelling radiation.
- g. Total upwelling radiation.
- h. Net radiation.

The last three measurements were taken with a pyrrometer sensitive to wavelengths between 0.3 and 60  $\mu$ m. Data were averaged over 5-, 30-, and 60-min intervals and stored in a third data logger CR 21.

30. The experiment was held in summer to provide high solar insolation resulting in large temperature variations.

#### Implementation of the Experiment

31. Preliminary data were collected 15, 19, 21, and 22 July, including trial runs of the Polycorder and calibrations of the radiation thermometers. For the calibration check, a heated surface of known emissivity was measured indoors with the radiation thermometers and a Wahl contact probe 350 x. The main experiment was run 4-7 Aug 1981.

32. Table 1 shows the periods when equipment was operational during the trial. Only the CR 21 data loggers performed well. The initial data loss was due to a programming error. The Polycorder turned out to be very difficult to program for this task and showed recurring data losses and wrong data points. The unit, which was in the first production run, will be recalled by the manufacturer to correct hardware problems. The Telatemp radiometer in its present configuration cannot be used in the continuous mode attempted here. The battery charger cannot keep up with a continuously operating instrument. No explanation can be offered for the occasional malfunction of the Heatspy radiometer.

33. Data evaluation will concentrate on the 24 hr of 6 Aug 1981 since they provide the most complete data set. The 6th of August was a hot day with a cumulus cloud cover varying between 20 and 60 percent.

## Table 1

15

## PART IV: RESULTS OF MEASUREMENTS

### Calibration Check of Radiation Thermometers

34. The Heatspy radiometer has a knob to manually zero the current in a bridge circuit. After initial start-up or changes in environmental temperature, this zero setting requires frequent adjustments. However, if the instrument is operating continuously, a change in environmental temperature will only temporarily unbalance the bridge. After a few minutes, the instrument will stabilize to the original zero setting. This permits an automatic operation of the instrument without frequent adjustments.

35. A black surface of emissivity  $\epsilon = 0.87$  was heated under thermostatic control in a closed room with a temperature of 22° to 23°C. Its temperature was measured with the Heatspy and Telatemp radiometers and with a Wahl contact probe 350 x. The contact probe was recently recalibrated by the manufacturer. The Heatspy was connected to a digital voltmeter to more accurately zero the bridge circuit before each measurement.

36. The laboratory was fully enclosed; hence, the effective emissivity of the background equalled one and the background temperature agreed with the room temperature. In this situation, Equation 7 can be applied easily to predict radiation temperatures from the kinetic temperature measured with the contact probe. This predicted radiation temperature should agree with the temperature measured by an ideal broadband detector. Figure 2 compares the prediction with the measurements from the two actual radiometers.

37. As can be seen from Figure 2, the three radiation temperatures agreed quite well--differences were about 1°C below 40°C. Agreement between Heatspy and contact probe was better than between Telatemp and contact probe. However, Telatemp readings were not as noisy as those from the Heatspy, even though the Heatspy was more carefully adjusted than in usual fieldwork.

38. Equation 7 used to predict radiation temperature assumed a

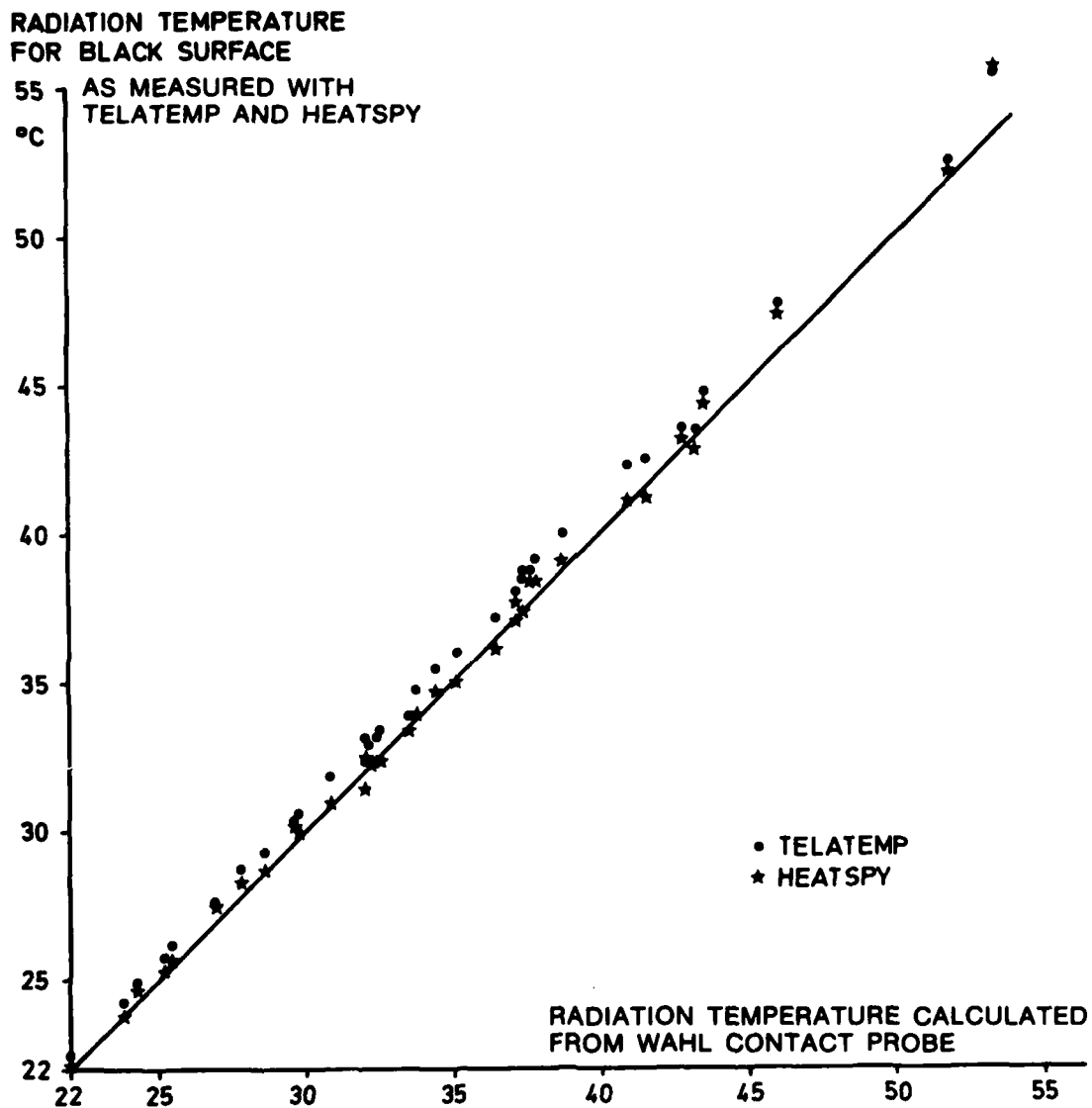


Figure 2. Calibration curve for Telatemp and Heatspy radiometer. Dots and stars are measured points. The diagonal is the line of equal radiation temperatures

broadband detector. The Heatspy radiometer is sensitive over a much broader band than the Telatemp radiometer. It is not surprising that agreement with the Heatspy measurements was better than with the Teletemp measurements. The Telatemp always read somewhat too high.

#### Short-Term Variation of Temperature

39. Temperature readings of the same thermistor averaged over 5, 30, and 60 min are shown in Figure 3. Even though asphalt has a high thermal mass, surface temperature can vary quite rapidly--up to 5°C within 5 min. The 30-min average still preserves the major fluctuations, but the 60-min average smoothes out most fluctuations.

40. Surface temperatures of asphalt and concrete had been measured with thermistors in Zweibrücken, Germany, in 1979 and 1980 (Gladen 1981). In 1979, data from thermistors were recorded as instantaneous values taken every 30 min. In 1980, thermistor data were 30-min averages taken every 30 min. Radiometric temperatures from hand-held radiometers and imagery devices represented instantaneous values at varying time intervals. It is obvious from Figure 3 that the different measurements cannot be expected to agree better than within a few degrees.

41. Computer models to predict surface temperature are available at WES (Balick et al. 1981). They require weather data as input and are usually run using hourly data as input. Clearly, such a computer run cannot predict the rapid variations of actual surface temperature.

#### Deployment of Thermistors

42. A comparison of thermistors deployed with and without a sun shield is shown in Figure 4 for 6 Aug 1981. Five-minute averages are plotted every 10 min. Figure 5 is an enlarged portion showing data every 5 min and includes the Heatspy measurements.

43. The radiometric measurement with the Heatspy can be trusted to accurately represent the time variation of the surface temperature

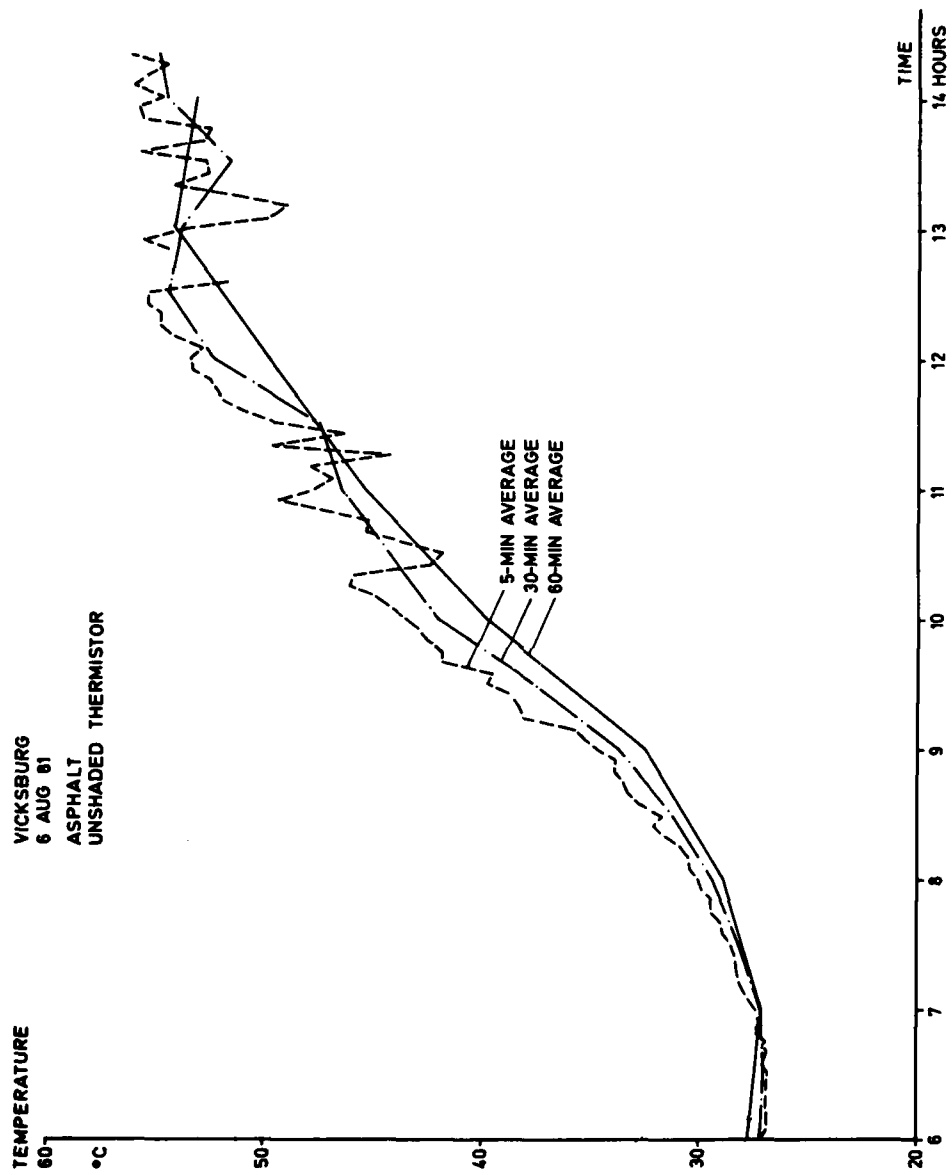


Figure 3. Asphalt surface temperatures: 5-, 30-, and 60-min averages

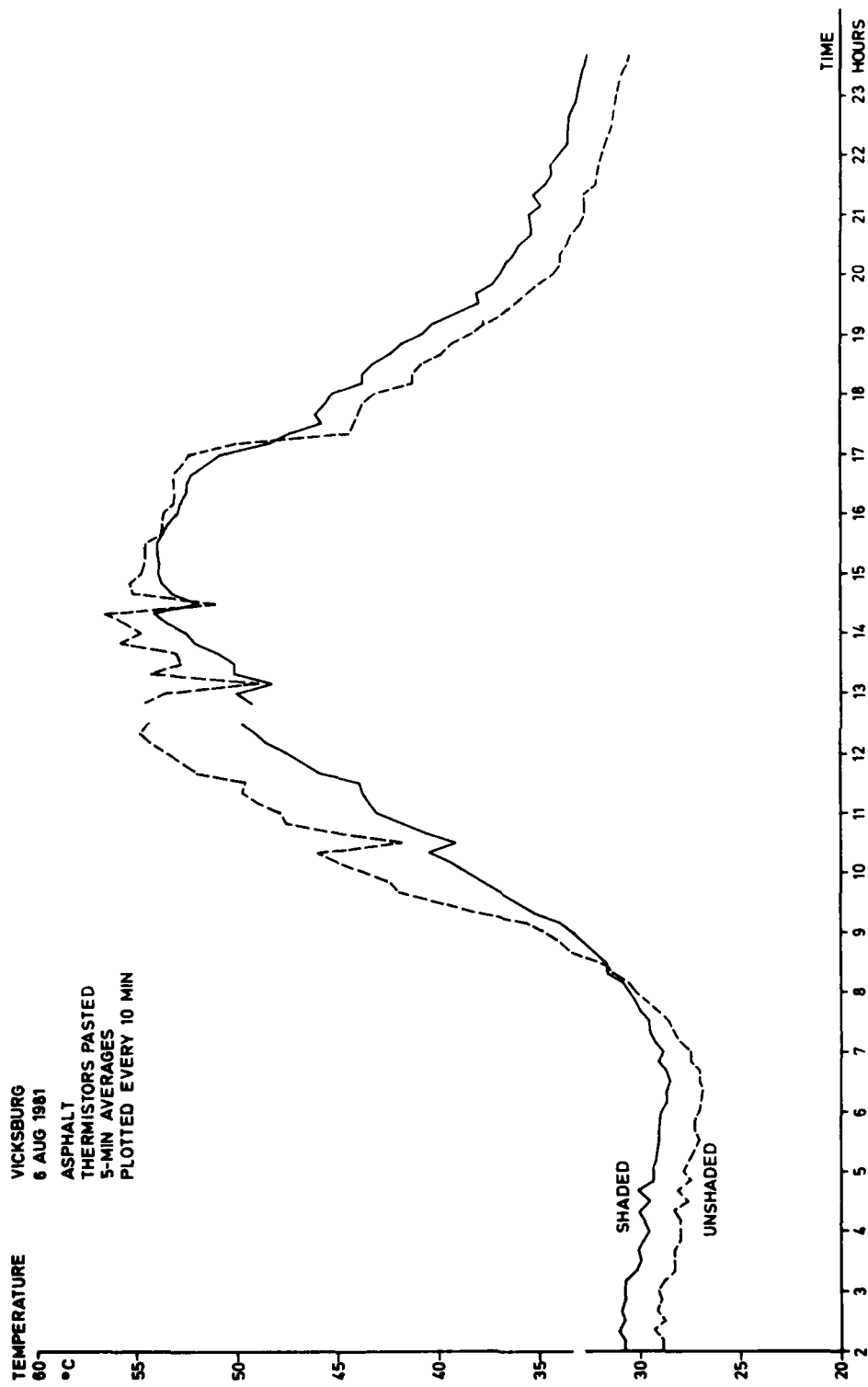


Figure 4. Comparison of shaded and unshaded thermistors

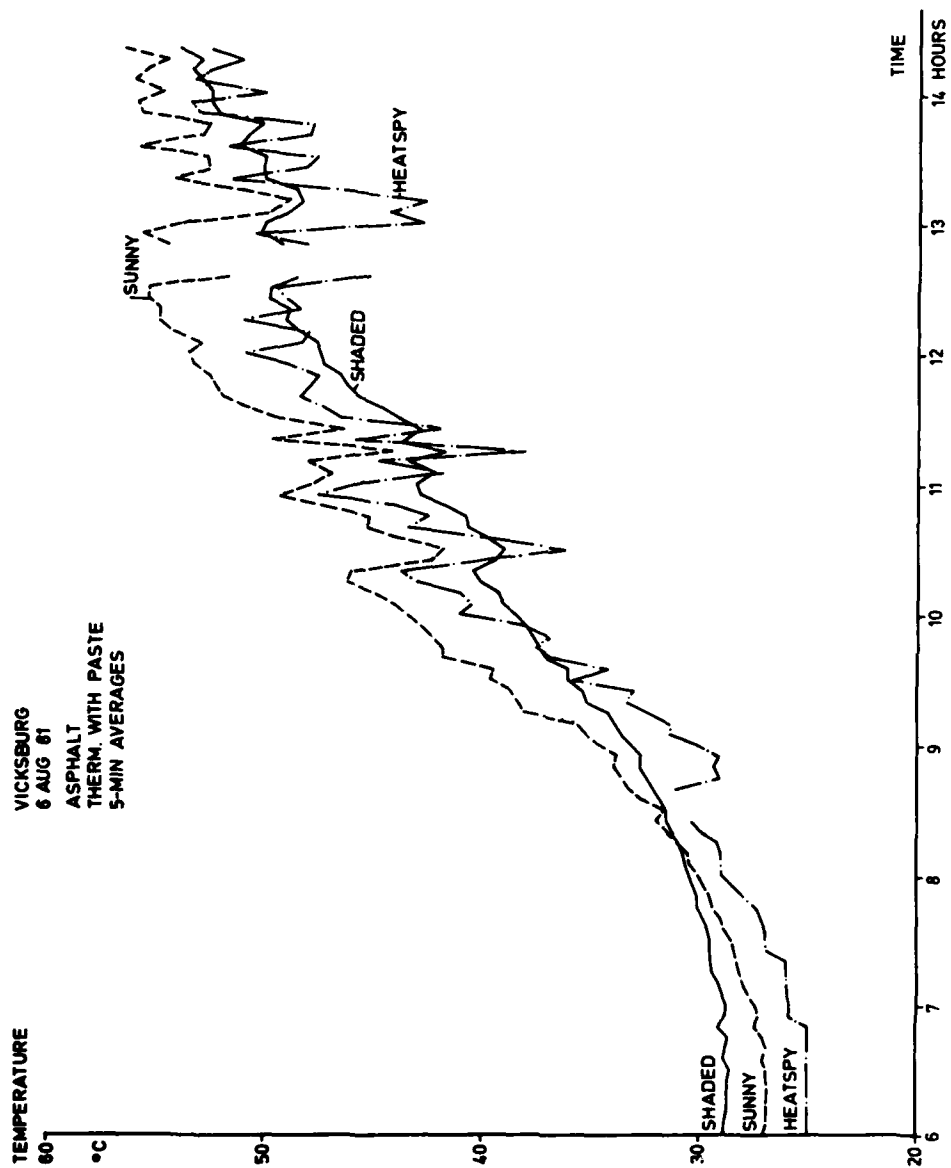


Figure 5. Comparison of shaded and unshaded thermistors with Heatspy data

since the radiometer responds within less than 1 sec. The unshielded thermistor follows the variations of the radiation temperature quite well (Figure 5), whereas the shielded thermistor averages out the more rapid variations. This is understandable because the shielded thermistor will be more affected by air temperature than by solar insolation. The good correlation between unshielded thermistor and Heatspy data leads to the conclusion that the thermistors for measuring surface temperature should be deployed without sun shields.

44. For the 1979 measurements in Zweibrücken, Germany, thermistors were deployed without sun shields, and in 1980 with sun shields. Figures 4 and 6 give an idea of the maximum errors expected from using sun shields. Figure 6 shows data for an almost completely cloud-free day and displays the overall trend better than Figure 4. The shaded thermistor remains 1° to 2°C warmer at night because of reduced radiation exchange. It rises slower in the morning and reaches a lower peak at a later time than the unshielded thermistor, which tracks more closely the solar insolation. It should be pointed out that the cases shown represent extremely hot days with high solar insolation. Differences for the moderate weather in central Europe, especially under cloudy skies, will be considerably smaller.

45. It has been observed that the silicone paste used to ensure good contact between thermistors and surface caused the surrounding surface area to be moist in some cases. Figures 7 and 8 show comparisons of thermistors deployed with and without this paste for the painted and the untreated asphalt. On the painted asphalt, there was no visible moisture around either thermistor. Both thermistors (Figure 7) yielded the same temperature at night. For high solar insolation, the thermistor with paste read 1° to 2°C higher. The thermistor without paste did not have good surface contact in this case, which probably accounted for the slightly lower temperature. In the case of untreated asphalt, there was some moisture around the thermistor with paste. According to Figure 8, this thermistor almost always read lower than the thermistor without paste. This difference may have resulted from the presence of moisture.

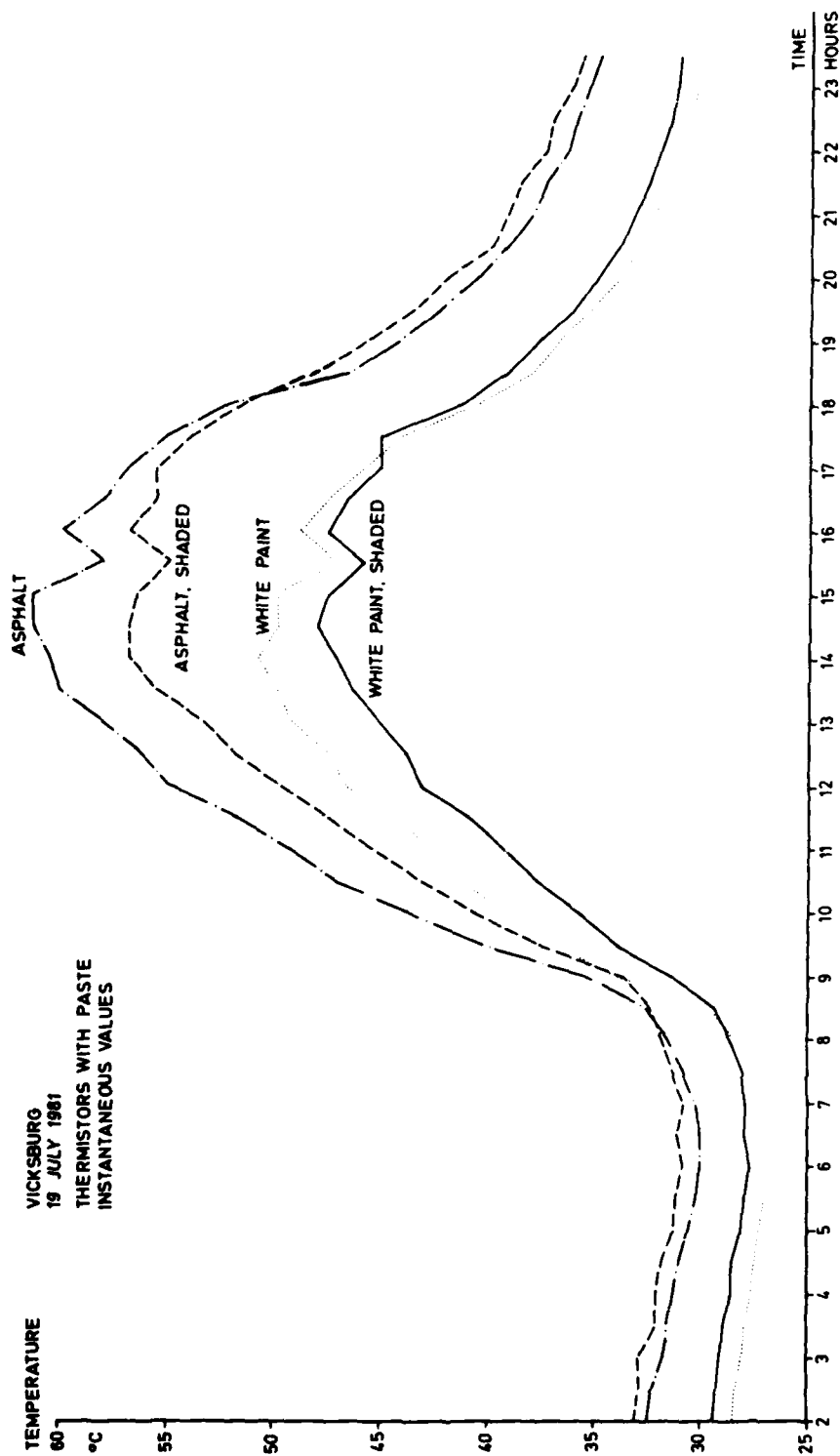


Figure 6. Comparison of shaded and unshaded thermistors for untreated asphalt and asphalt with white paint

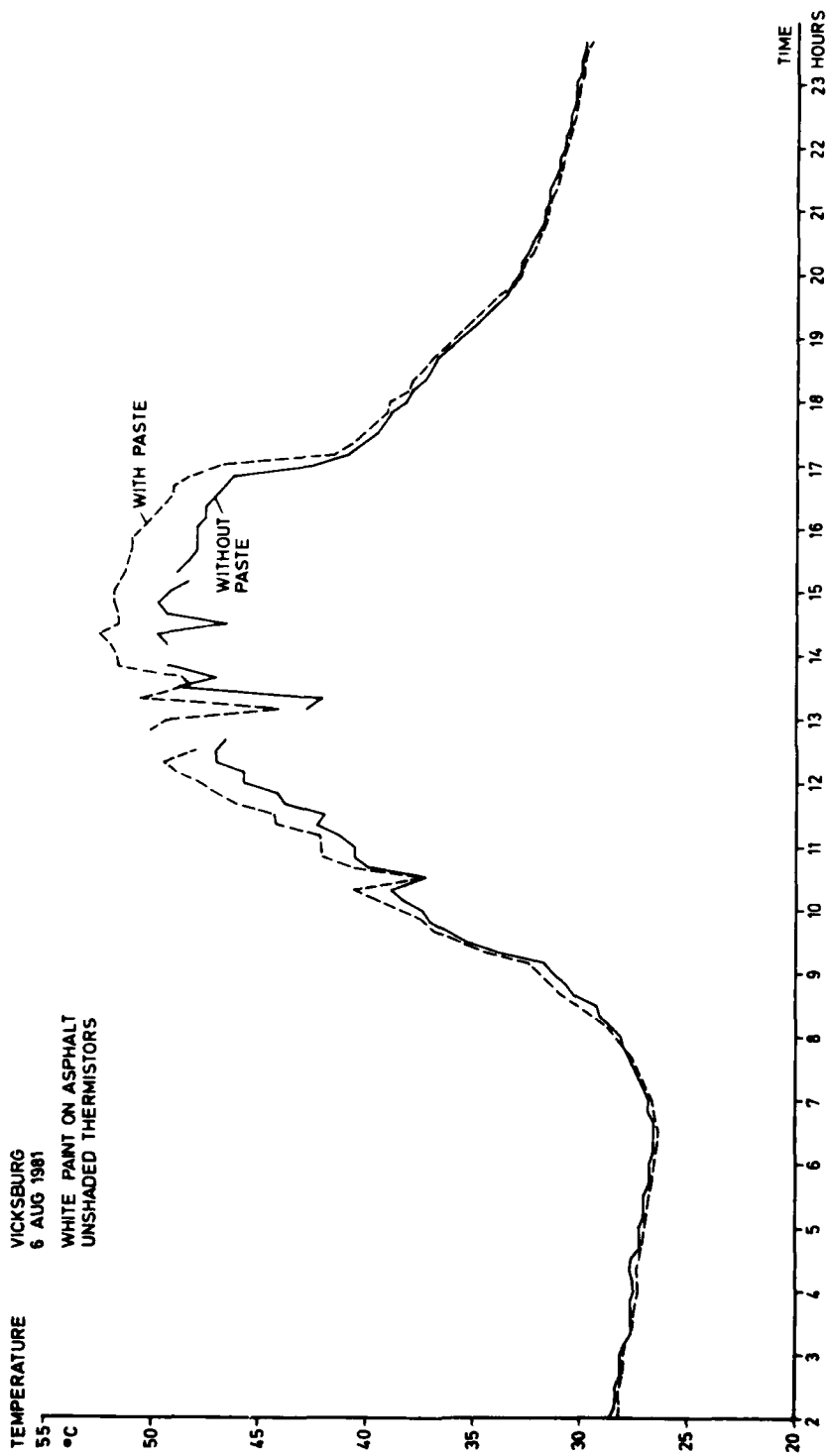


Figure 7. Comparison of thermistors with and without silicone paste deployed on painted asphalt

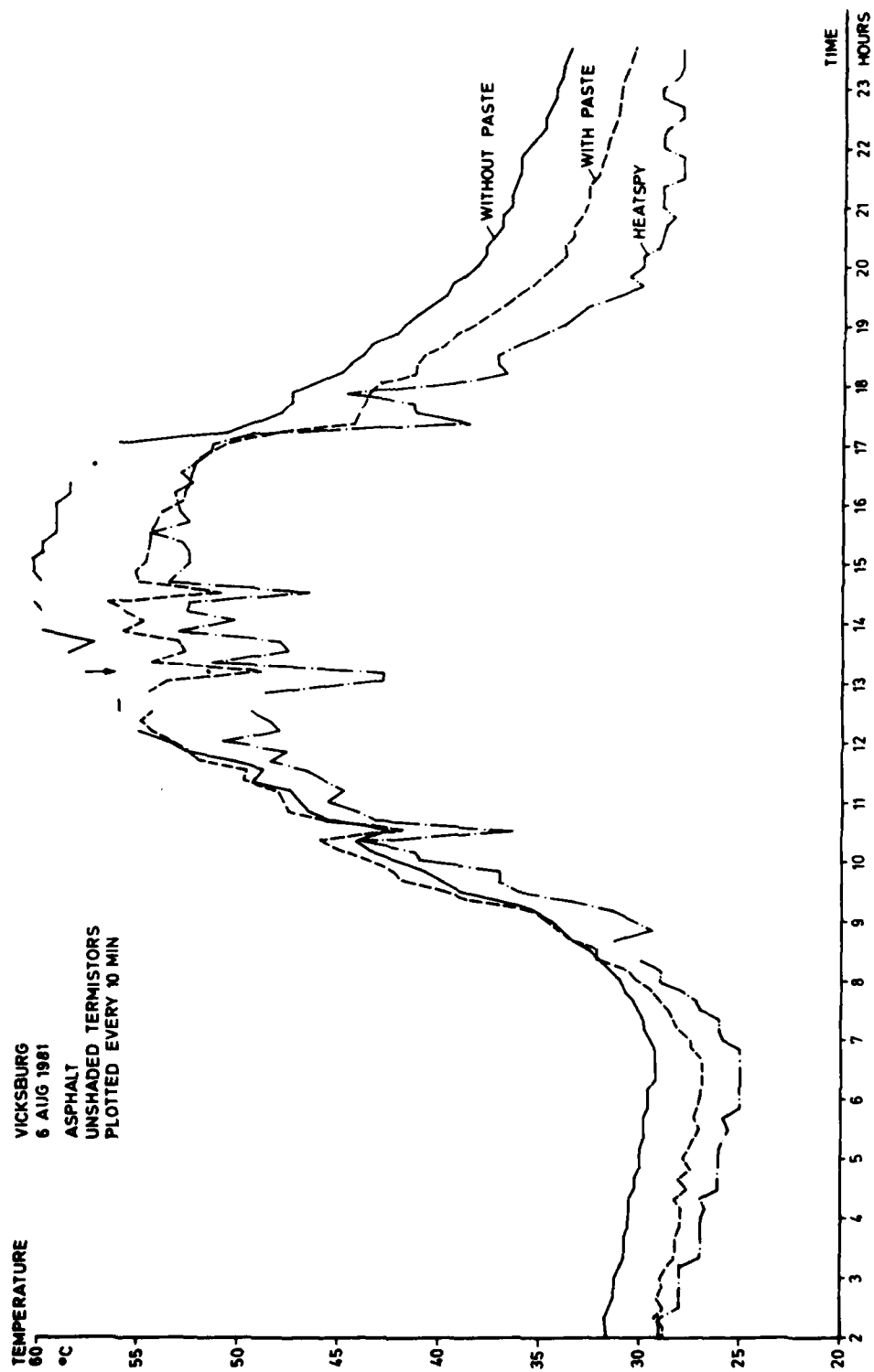


Figure 8. Comparison of thermistors with and without silicone paste on untreated asphalt.  
Data from Heatspy radiometer are included

### Field Performance of Radiation Thermometers

46. As has been mentioned, both radiation thermometers failed repeatedly during the field experiment. The only longer period when both of them worked occurred on 5 Aug 81 between 1000 and 2230 hr. Results for this period are presented in Figure 9. The data from the Heatspy displayed more fluctuations than those from the Telatemp or the thermistor. There was considerable noise in the Heatspy measurements. The Telatemp measurements were smoother, but read higher in many cases. These are the same conclusions as drawn from the laboratory comparison in paragraphs 37 and 38.

47. Background for the horizontal asphalt target was primarily the sky. Sky temperature was measured during daytime, but not at night. Temperatures for clear sky near the zenith were 17° to 20°C from the Heatspy and -2° to 0°C from the Telatemp. This large difference was due to the different spectral sensitivity of the radiometers. While the Telatemp is sensitive only to radiation in the infrared window between 8 and 14  $\mu\text{m}$ , the Heatspy is sensitive to wavelengths between 4.8 and 20  $\mu\text{m}$ . Predictions of the clear sky temperature for the same day from a broadband formula (Jacobs 1980) varied between 10° and 21°C. This differed from both measurements, but agreement was better with the broadband Heatspy than with the narrowband Telatemp.

### Comparison of Kinetic and Radiation Temperatures

48. All plots for thermistors in Figures 3 to 9 show kinetic temperatures as obtained from the data logger. For a quantitative comparison with the results from the radiation thermometers, the kinetic temperatures should be converted to radiation temperatures. Since the information required to apply Equation 8 is not available, Equation 7 has to be used:

$$T_r^4 = \epsilon T^4 + (1 - \epsilon) T_B^4 \quad (7, \text{bis})$$

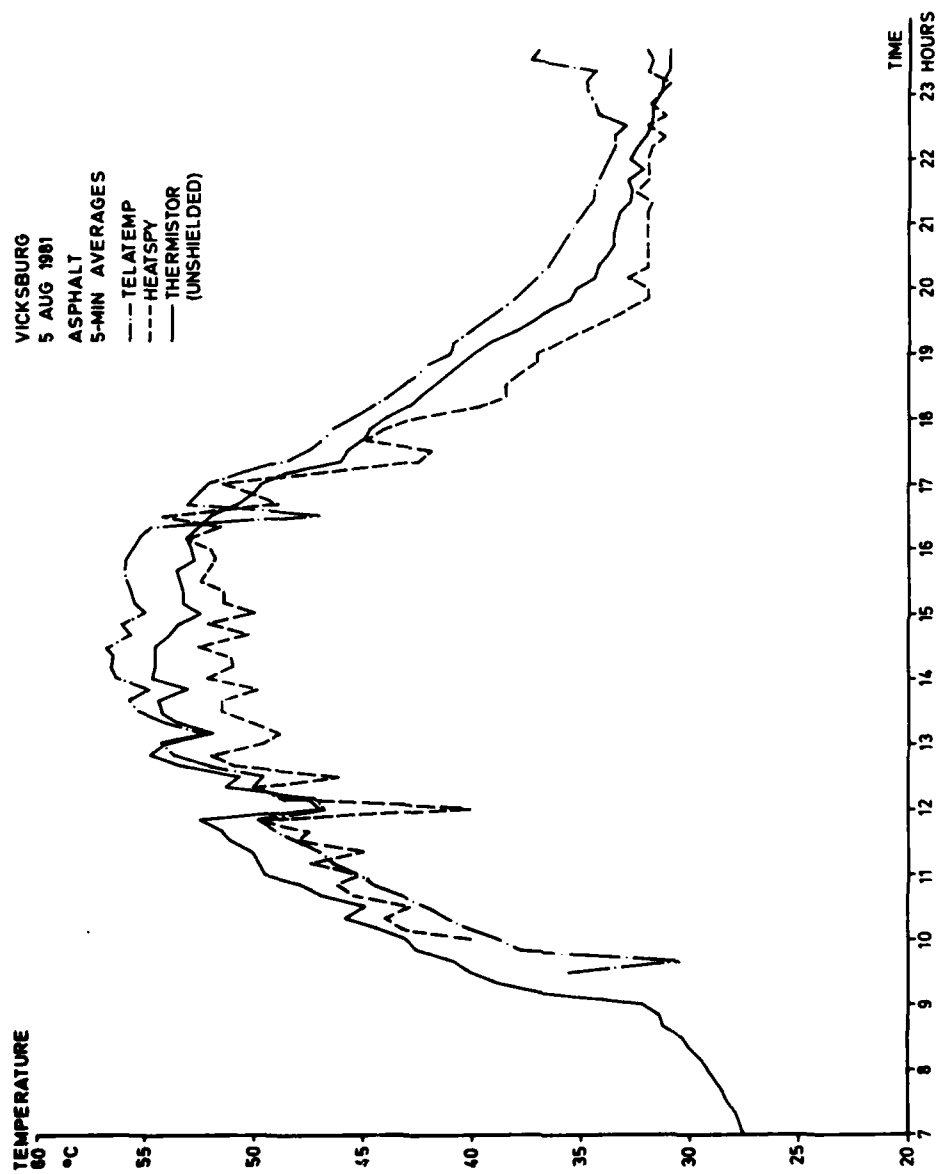


Figure 9. Comparison of Heatspy and Telatemp radiometers for untreated asphalt.  
Thermistor data are included for reference

The emissivity of the asphalt plot is estimated to be 0.90 to 0.95.

49. Radiation temperatures were calculated for two extreme cases of relatively low and high target temperatures on 6 Aug 1980 using the sky temperatures measured with the Heatspy (HS) and Telatemp (TL):

Time hr	Kinetic Temperature °C	Sky Temperature, °C		Predicted Radiation Temperature, °C			
				$\epsilon = 0.90$		$\epsilon = 0.95$	
		HS	TL	HS	TL	HS	TL
8:30	32	20	0	30.9	29.2	31.4	30.6
15:30	55	17	-2	51.8	50.5	53.4	52.8

The tabulation shows that radiation temperatures are lower than kinetic temperatures, but that the difference is small for a surface of high emissivity. It predicts the Heatspy to read between 1.1° and 3.2°C lower than the thermistor for an emissivity of 0.90, and between 0.6° and 1.6°C lower for an emissivity of 0.95. Radiation temperatures from the Telatemp are expected to be lower than those from the Heatspy.

50. Figure 8 compares the kinetic temperatures from two unshaded thermistors on asphalt with the radiation temperatures from the Heatspy. Heatspy temperatures were always lower than thermistor temperatures, which is expected from the above tabulation. Temperature differences between the Heatspy and the thermistor with paste were of the same magnitude as predicted, whereas the differences between the Heatspy and the thermistor without paste were considerably larger. This result would support the deployment of the thermistor with paste.

51. Comparisons of the two radiometers and an unshaded thermistor for 5 Aug 1981 were presented in Figure 9. Heatspy measurements read again a few degrees lower than the thermistor, in agreement with the predictions of paragraph 49 and the measurements for 6 Aug 1981 (Figure 8). The Telatemp readings, however, were mostly higher than both the thermistor and the Heatspy. The readings should have been lower than those from the thermistor since radiation temperatures are always less than or equal to kinetic temperatures under a low temperature sky. The readings should also have been lower than those from the Heatspy

because of the narrower spectral sensitivity as found in paragraph 49. The reason for this unexpected result is unknown; however, the difficulty of operating the instrument continuously that was mentioned earlier (paragraph 32) may have caused the accuracy problems.

## PART V: COMPARISON WITH MODEL PREDICTIONS

52. The day with the most complete data set, 6 Aug 81, was a day with intermittent cloud cover causing strong fluctuations in solar radiation (Figure 10). Comparison of Figure 10 with Figure 5 shows that most of the solar fluctuations are reproduced in fluctuations of the surface temperature. An exception occurred after 1000 hr, when there was a tree shadow on the solarimeter, but not on the target surface.

53. The solar fluctuations made this day not very suitable for model verification, since hourly input data usually are used in the model. Figure 11 shows 60-min average values for air temperature and solar radiation, two major inputs for the TSTM model, together with the temperature prediction of the model for asphalt. As can be seen, the predicted temperature follows the variations of both air temperature and solar radiation.

54. Figure 12 compares predicted temperature with measured temperatures from the shaded and unshaded thermistor. The time variations of the unshaded thermistor and the model agreed very well, whereas the shaded thermistor showed a distinctly different time behavior. It rose and fell at a slower rate and reached its daytime peak later. This same discrepancy was noted in the evaluation of the Zweibrücken 1980 data and prompted the experiment reported herein. An attempt had been made to use the 1980 thermistor measurements in Zweibrücken of concrete to validate the TSTM model. The model was run many times with different material parameters to obtain agreement between predicted and measured temperatures. The model turned out to be remarkably stable and never produced a time behavior in line with that of the shielded thermistor. Since the fault has now been found to lie with the measurements, the stability of the model supports confidence in the model.

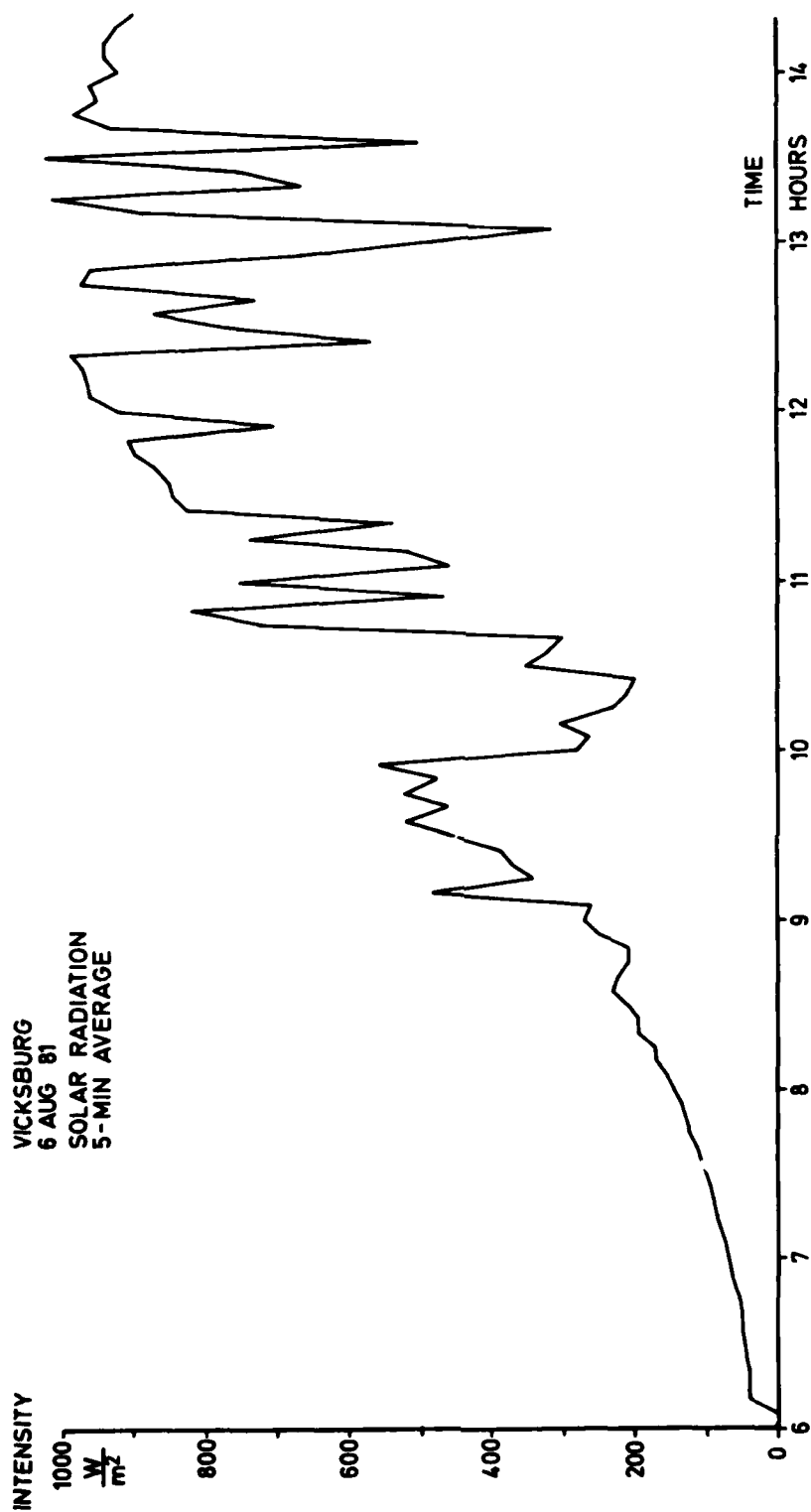


Figure 10. Fluctuations in 5-min averages of solar radiation

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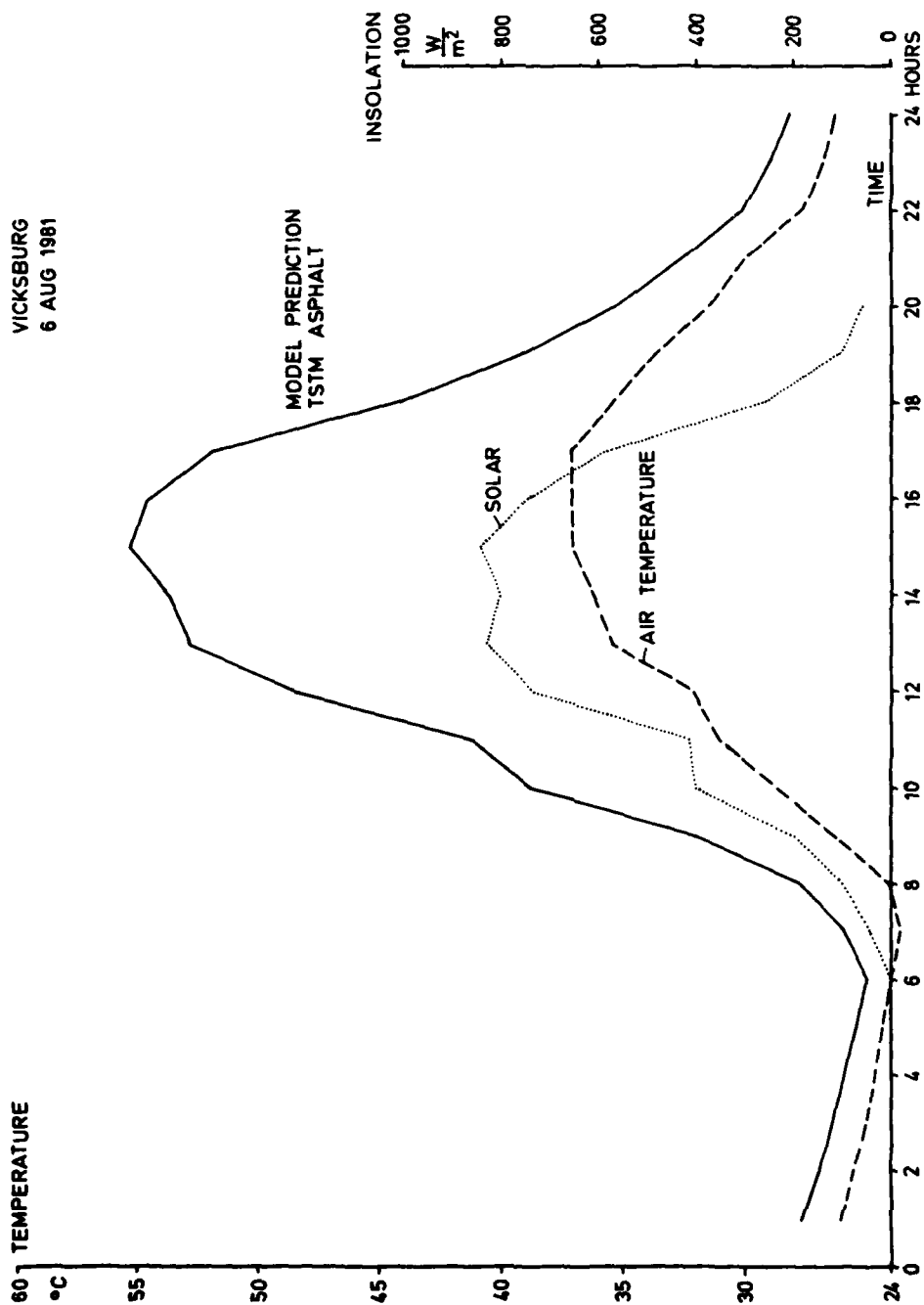


Figure 11. Terrain Surface Temperature Model (TSTM) for asphalt; 60-min averages of solar radiation and air temperature are inputs for the model. Model prediction is asphalt surface temperature

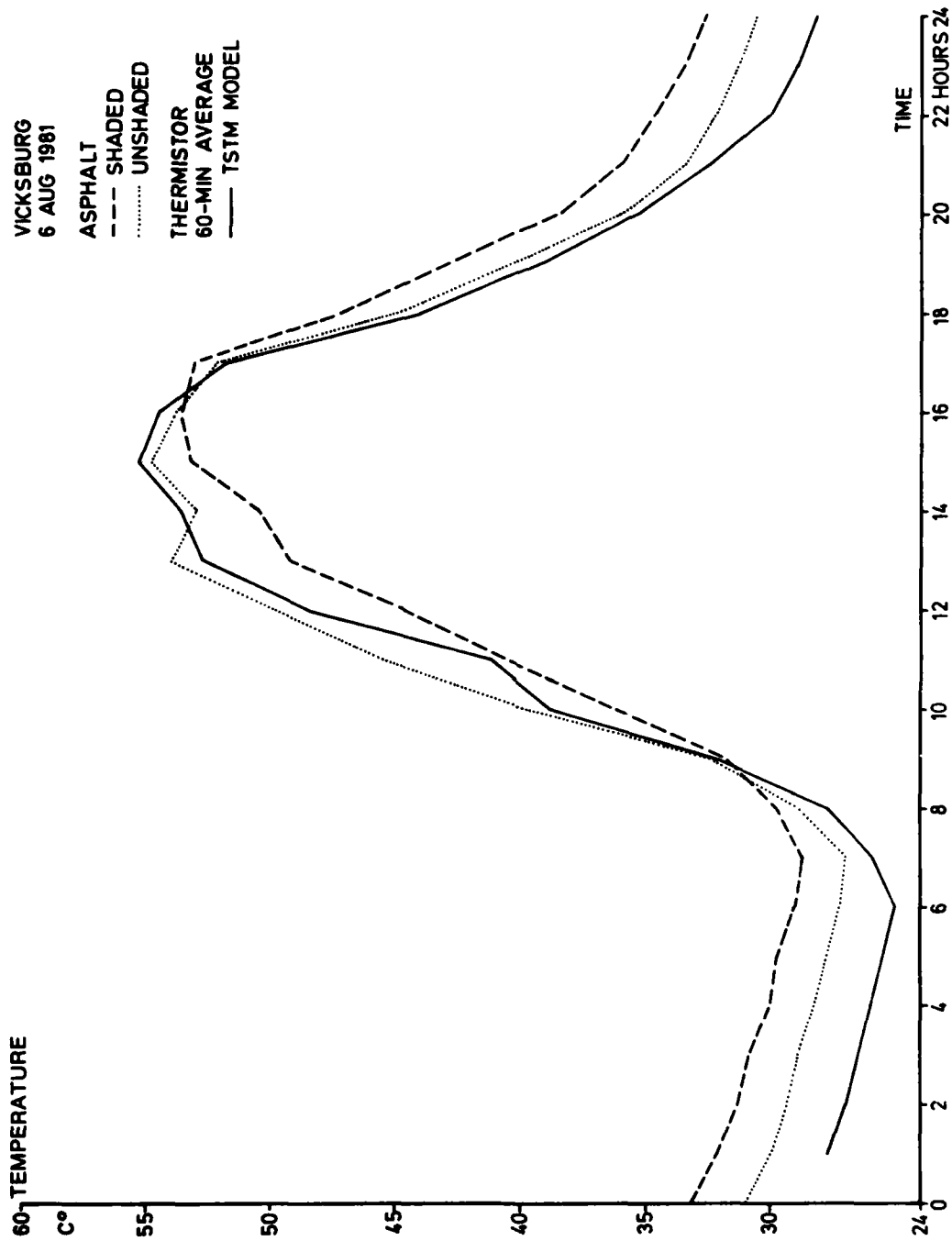


Figure 12. Comparison of predicted and measured surface temperatures

## PART VI: CONCLUSIONS AND RECOMMENDATIONS

### Conclusions

55. The thermistors used here and in previous measurements had a cylindrical shape and were designed to measure temperatures in a volume of gas, liquid, or aggregate. It has been shown that they can be used to measure surface temperature although they disturb the surface to be measured.

56. Rapid fluctuations in surface temperature were observed even for targets with a large thermal mass. It follows then that, in comparisons of temperature measurements that were not taken simultaneously and at the same spot, agreement can be expected only within a few degrees centigrade.

57. The use of different types of thermometers introduces additional variability. Readings from radiation thermometers depend on target emissivity, background temperature, and spectral range of the detector. Readings from different instruments can differ by several degrees centigrade.

58. Converting measured kinetic temperatures to radiation temperatures is not necessary for targets of high emissivity ( $\epsilon > 0.9$ ), since the correction factor is within the differences noted above.

59. The WES computer models to predict surface temperature are usually run using hourly weather data as input. The models interpolate the weather data linearly between the input points. For a situation of intermittent cloud cover, this is not a good approximation to the actual weather conditions affecting target temperature. With these input limitations, even a perfect model could not accurately predict actual surface temperatures. It follows that it is difficult to validate such a model. However, this is not at all an argument against the models. They were developed to predict the general behavior of targets and backgrounds in the future--a situation where no specific weather information is available, but where only typical weather situations can be assumed.

### Recommendations

60. Thermistors for measuring surface temperature should be deployed without a sun shield and with a means for ensuring good contact to the surface. The hygroscopic silicone paste used here was not satisfactory for long-term measurements. An epoxy glue used previously destroyed the thermistor upon removal. Taping the thermistor to the surface as tried here did not always ensure good contact and disturbed an unnecessarily large part of the surface to be measured. Other means for attachment should be investigated.

61. When using the Heatspy radiometer, more care should be exercised in zeroing the instrument. It is not sufficient to get a zero reading on the display. A better balance is obtained when the + sign on the display vanishes. It was found very beneficial to automate the radiometer reading. This ensured measurements of the same spot under the same viewing angle at well-defined intervals. A disadvantage of the method was that only one surface could be measured at a time.

62. In any project measuring surface temperatures outdoors, regular measurements of sky temperature should be included.

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Bibliography: p. 36.

1. Camouflage (Military science). 2. Temperature--Measurements. 3. Thermometers and thermometry.  
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